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## 1 Performance analysis of wind fence models when used for truck protection under 2 crosswind through numerical modelling

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4 A. Alonso-Estébanez<sup>1,\*</sup>, J.J. Del Coz Díaz<sup>2</sup>, F.P. Álvarez Rabanal<sup>3</sup>, P. Pascual-Muñoz<sup>4</sup>

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6 <sup>1</sup>Dept. of Transport, Project and Process Technology, ETSICCP, Univ. of Cantabria, Ave. Castros s/n, 39005 Santander, Spain. E-mail: alonsoea@unican.es.

7  
8 <sup>2</sup>Dept. of Construction, EPSIG, Univ. of Oviedo, Departmental Building 7, 33204 Gijón, Spain. E-mail: juanjo@constru.uniovi.es.

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10 <sup>3</sup>Dept. of Construction, EPSIG, Univ. of Oviedo, Departmental Building 7, 33204 Gijón, Spain. E-mail: felipe@constru.uniovi.es.

11  
12 <sup>4</sup>Dept. of Transport, Project and Process Technology, ETSICCP, Univ. of Cantabria, Ave. Castros s/n, 39005 Santander, Spain. E-mail: pascualmp@unican.es.

### 13 Abstract

14 This paper is focused on truck aerodynamic analysis under crosswind conditions by means of numerical  
15 modelling. The truck was located on the crest of an embankment during the study. In order to analyze the  
16 performance of three wind fence models, the truck's aerodynamic coefficients were obtained and  
17 compared in two different situations either with or without the wind fences installed. In addition, the  
18 effect of both height and porosity of wind fence models on the aerodynamic coefficients acting on truck  
19 with respect to separation distance between the truck and the wind fence, was analyzed. A finite volume  
20 (or computational fluid dynamic) code was used to carry out the numerical modeling. The Reynolds-  
21 averaged Navier–Stokes (RANS) equations along with the  $k-\omega$  SST turbulence model were used to  
22 predict the behavior of turbulent flow. With respect to the results, the influence of the distance on the  
23 rollover coefficient is soft for all height values studied except for the lowest value (1m of fence height),  
24 where the maximum value of rollover coefficient was obtained for the truck position closer to the fence.  
25 Regarding fence porosity, its effect on rollover coefficient is stronger for truck positions on road closer to  
26 the wind fence model.

27 **Keywords:** Crosswind; truck vehicle aerodynamics; wind fence; embankment; CFD simulations; wind  
28 tunnel tests.

### 30 1. Introduction

31 Under strong crosswind conditions, vehicle stability is adversely affected and as a consequence the risk of  
32 having an accident is increased. This issue has motivated the development of wind warning systems  
33 (Hoppmann et al., 2002; Delaunay et al., 2006) and new guidelines/regulations (Tielkes et al., 2008; Imai  
34 et al., 2002) in order to safeguard crosswind safety. With this goal, wind fences have also been used in  
35 bridges and embankments as in Imai et al. (2002). Another aspect is that blowing snow hinders driving  
36 because the drivers' visibility is reduced and ice formation is caused (Tabler and Meena, 2007;  
37 Matsuzawa et al., 2005). Thus, in exposed windy and snowy locations, wind fences have been adopted as  
38 control measures for protecting roads. In different locations around the world several accidents due to  
39 crosswind and blowing snow have been registered and analyzed (Imai et al., 2002; Shao et al., 2011;  
40 Matsuzawa et al., 2005).

\*Corresponding author. Tel.: +34 942 200894; fax: +34 942 201703.

41 There are many works on wind fence performance within other fields of application apart from traffic  
42 safety. Bitog et al. (2009) analyzed the effect of different building parameters of wind fences on  
43 preventing the generation and diffusion of dust from sandy land. In open storage yards, the stockpiles are  
44 often eroded by the wind and as countermeasures are needed to avoid the dispersion of particles, wind  
45 fences are used in many locations (Yeh et al., 2010; Santiago et al., 2007; Park and Lee, 2001). Trees may  
46 also be used as windbreaks to prevent odour dispersion in places like livestock farms (Lin et al., 2007).  
47 Another application of wind fences is aimed at improving external comfort in urban open spaces such as  
48 parks, playgrounds and recreational fields (Li et al., 2007).

49 Some studies have focused on optimizing different parameters of the snow fence geometry to improve its  
50 performance. Dong et al. (2007) studied the influence of porosity on the fence's shelter efficiency,  
51 measuring wind velocity and analyzing streamline patterns behind the fence. This research found that the  
52 optimal porosity was around 0.2 or 0.3, since for higher values of porosity, bleed flow dominates and for  
53 lower values of porosity, reversed flow becomes significant. Other parameters such as wind fence height  
54 and gap between the ground and the fence have been also studied. Kim and Lee (2002) investigated the  
55 flow field behind porous fences for four values of gap ratios, and the best protection against the wind was  
56 found for a gap ratio of 0.1H (H being the height of the fence). Imai et al. (2002) obtained the  
57 aerodynamic coefficients of a vehicle through wind tunnel test for several values of the height and  
58 porosity of the fence. The result indicated that for higher height of fence, keeping the porosity constant,  
59 the possibilities of overturning diminished. The influence of the distance between the vehicles and a wind  
60 fence model consisted of boards on the aerodynamics coefficient of rail and road vehicles, was studied in  
61 Zhu et al. (2012) for four positions of vehicle along the cross section of bridge. Also, Guo et al. (2015)  
62 estimated the aerodynamic coefficients acting on rail vehicle with different wind fence configurations  
63 installed on a bridge for two positions of vehicle on the bridge (windward and leeward). In both studies,  
64 the aerodynamic coefficients of vehicles diminished with the distance between the vehicle and the wind  
65 fence.

66 So far, wind fence performance has been evaluated by different techniques such as numerical simulation  
67 (CFD), wind tunnel test and field experiments. Wind tunnel tests were carried out to investigate how the  
68 wind fence improves vehicle stability under cross wind conditions when a vehicle passes through the  
69 wake of a bridge tower (Agentini et al., 2011; Bocciolone et al., 2008). For instance, Santiago et al.  
70 (2007) used numerical simulation in addition to wind tunnel tests in order to determine an optimum  
71 porosity for sheltering effect of an isolated windbreak. While other research such as Tuzet and Wilson  
72 (2007) and Torita and Satou (2007) performed field studies about the wind shelter provided by natural  
73 windbreaks.

74 In this paper, shelter efficiency of three wind fence models installed on an embankment is analyzed by  
75 obtaining the aerodynamic coefficients acting on the truck. Particularly, the first aim of this research  
76 consists in analyzing the influence of the geometry design of wind fences on truck aerodynamics. The  
77 second aim is to demonstrate the use of CFD codes to solve this kind of problems, being validated with  
78 experimental data. On the other hand, the first part of the paper describes the methodology applied to

79 carry out the numerical simulations and the second section indicates and discusses the main results of the  
 80 study. The last section specifies the main conclusions based on the results obtained.

## 81 2. Numerical procedure

82 The ANSYS FLUENT Academic Research software version 15 was used for solving the fluid-structure  
 83 interaction problem.

### 84 2.1. Formulation of the model

85 The CFD codes numerically solve the governing equations of a turbulent flow, which are the continuity  
 86 equation and Reynolds average Navier-Stokes (RANS) momentum, equation indicated in Eq. (1) and Eq.  
 87 (2) (Mathieu and Scott, 2000; Pope, 2000; Tu et al., 2008). In order to obtain these equations, the  
 88 Reynolds decomposition was used.

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial}{\partial t} (\rho \bar{u}_i) + \frac{\partial}{\partial x_j} (\rho \bar{u}_i \bar{u}_j) = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \rho \overline{u'_i u'_j} \right] \quad (2)$$

89 The term  $-\overline{\rho u'_i u'_j}$  is a turbulent stress or Reynolds stress and states the correlations among the  
 90 fluctuating velocity components. This term depicts additional unknowns in the time-averaged Navier-  
 91 Stokes momentum equation. Therefore, for closing the above system of equations, new expressions which  
 92 model the Reynolds stresses are required. These expressions will be introduced by mean of called  
 93 turbulence models.  
 94

95 The SST  $k-\omega$  turbulence model (Menter 1993, 1994) was used in the present work because it provides  
 96 good performance when dealing with low Reynolds issues, adverse pressure gradients and separating  
 97 flow regions. This turbulence model combines the standard  $k-\varepsilon$  model and the  $k-\omega$  model, which  
 98 retains the properties of  $k-\omega$  close to the wall and gradually blends into the standard  $k-\varepsilon$  model away  
 99 from the wall. Nevertheless, the numerical results were also obtained by using the standard  $k-\varepsilon$  model  
 100 in order to check the better performance of SST  $k-\omega$  to estimate the aerodynamic loads acting on the  
 101 truck model analysed. The standard  $k-\varepsilon$  model was selected because it is the most widely validated  
 102 turbulence model and used for industrial applications (Andersson et al., 2011; Ranade, 2002). The  
 103 standard Menter SST two-equation model (written in conservation form) is provided by the following two  
 104 equations, the first equation corresponding to the turbulence kinetic energy,  $k$ , and the second equation for  
 105 the specific dissipation rate,  $\omega$ :

$$\frac{\partial k}{\partial t} + \bar{u}_j \frac{\partial k}{\partial x_j} = P_k - \beta^* k \omega + \frac{\partial}{\partial x_j} \left[ (v + \sigma_k \nu_T) \frac{\partial k}{\partial x_j} \right] \quad (3)$$

$$\frac{\partial \omega}{\partial t} + \bar{u}_j \frac{\partial \omega}{\partial x_j} = \alpha S^2 - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[ (v + \sigma_\omega \nu_T) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_1) \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i} \quad (4)$$

106

107 The equations have been written to be in an appropriate conservation form (Zienkiewicz et al., 2005).  
 108 Note that it is generally recommended to use a production limiter for the turbulence kinetic energy.  
 109 Therefore, in this research work, the term  $P_k$  in the Eq. (3) is replaced by:

$$P_k = \min\left(\overline{\tau_{ij} \frac{\partial u_i}{\partial x_j}}, 10\beta^* k\omega\right) \quad (5)$$

110 Where the stress tensor,  $\overline{\tau_{ij}}$ , can be written as:

$$\overline{\tau_{ij}} = \mu_T \left( 2S_{ij} - \frac{2}{3} \frac{\partial \overline{u_k}}{\partial x_k} \delta_{ij} \right) - \frac{2}{3} \rho k \delta_{ij} \quad (6)$$

111 and the kinematic eddy viscosity is computed from:

$$\nu_T = \frac{a_1 k}{\max(a_1 \omega, \Omega F_2)} \quad (7)$$

112 More detailed information about constants or closure coefficients can be found in Menter (1993), (1994)  
 113 and Ansys, (2015).

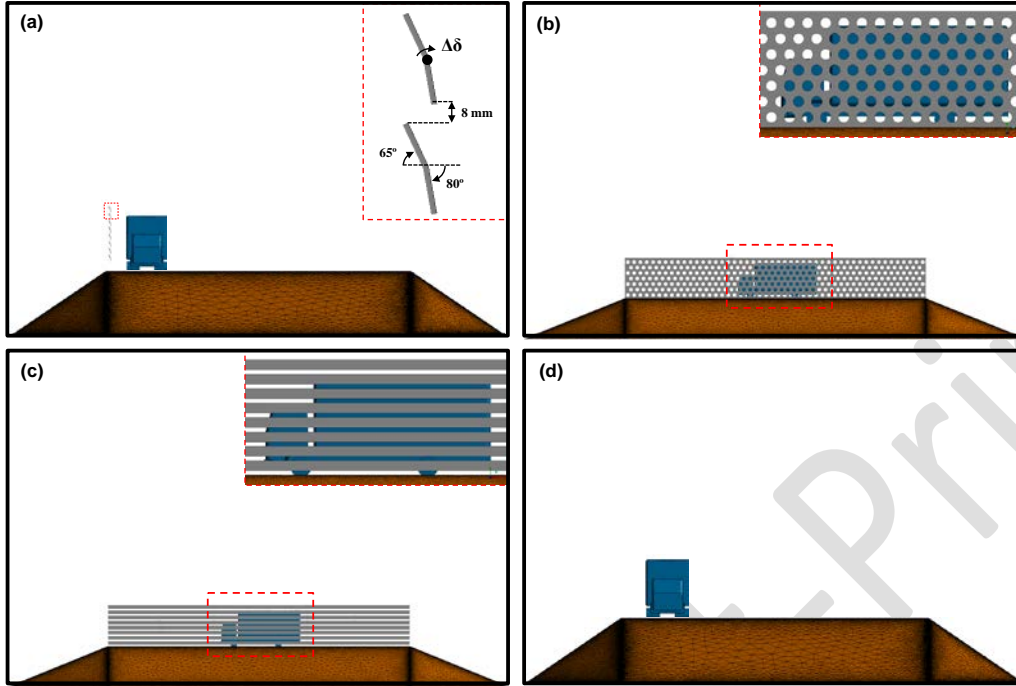
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## 115 **2.2. Wind fence models and aerodynamic coefficients**

116 The embankment configuration, as shown in Fig. 1, speeds up the air flow on the windward slope  
 117 (Bitsuamlak et al., 2004). Therefore, in this situation the vehicles are more likely to suffer a rollover  
 118 accident than in other locations for a specific yaw angle (angle between relative wind speed and path of  
 119 vehicle) range (Schober et al., 2010). Accordingly, the embankment configuration is a scenario where the  
 120 security of traffic could be significantly improved by installing wind fences. This was the reason for  
 121 choosing this scenario to carry out the study about performance of three models of wind fences (Fig. 1).  
 122 In the numerical simulation, the models (wind fences, embankment and truck) were scaled down 1/10  
 123 with respect to the full scale prototype as in Cheli et al. (2011a\b). Detailed information about the  
 124 dimensions of both the truck and embankment can be found in Cheli et al. (2011a) and Cheli et al.  
 125 (2011b) respectively. Specifically, the aerodynamic coefficient acting on truck was obtained for a wind  
 126 fence with plates and two wind fences with different shapes of the open area (circular and rectangular).  
 127 Also, the aerodynamic loads were calculated for the truck located on the embankment without protection.  
 128 This case is based on the wind tunnel test developed by Cheli et al. (2011b), allowing analyze the  
 129 goodness of fit between the numerical model and an experimental reference. Therefore, this case was  
 130 solved previously to the models including the different wind fence types studied.

### 131 **1.1. Aerodynamic forces and moments**

132 Particularly, the following aerodynamic forces and moments were obtained: side force ( $F_S$ ), lift force ( $F_L$ )  
 133 and rollover moment ( $M_R$ ) (Fig. 2). The side and lift forces acting on the truck were calculated by  
 134 integrating the pressure distribution over the surface of truck. The rollover moment is the sum of the  
 135 moments from the side and the lift force above point O.



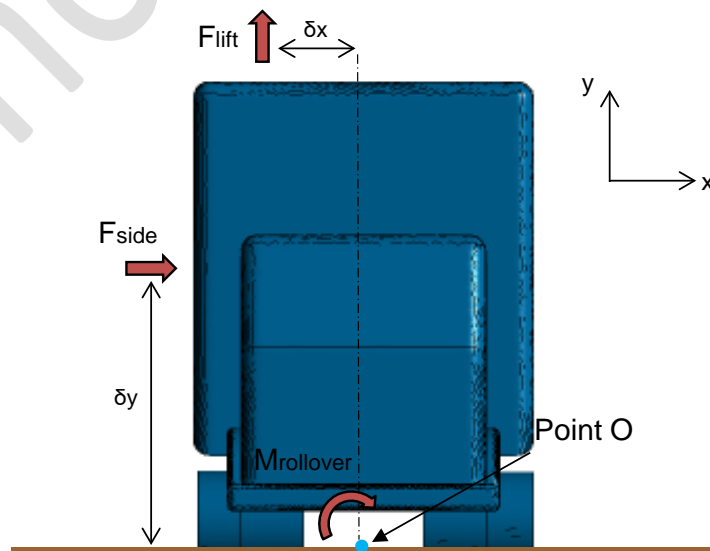
136  
137  
138 **Fig. 1. Models studied (1:10 scale): (a) Wind fence model with plates; (b) Wind fence model with circular holes; (c) Wind fence model with rectangular slits and (d) Without wind fence model.**

139 Once the aerodynamic loads were calculated, they were rendered dimensionless coefficients using the  
140 following expressions:

$$C_S = \frac{F_S}{\frac{1}{2} \rho U^2 A_S} \quad C_L = \frac{F_L}{\frac{1}{2} \rho U^2 A_S} \quad C_R = \frac{M_R}{\frac{1}{2} \rho U^2 A_S H} \quad (8)$$

141 where  $\rho$  is the density of the air,  $A_S$  is the side area of the truck,  $H$  is the reference height (height of box  
142 truck) and  $U$  is the mean streamwise wind speed measured at 0.6 m from the ground in the CFD model.

143 Both the truck model and the embankment studied in these CFD models have the same dimensions of the  
144 1:10 scale model presented in Cheli et al. (2011a\b).



145  
146 **Fig. 2. Sketch of aerodynamic loads studied under crosswind conditions.**

## 1.2. Grid, boundary conditions and design of experiment

The 3D geometry for the computational domain defined to solve the fluid behavior around the bluff bodies (truck, wind fences and embankment) is shown in Fig. 3. The inlet and outlet of air flow were located at least  $8.3H_{obs}$  (being  $H_{obs}$  the obstacle height) and  $19.3H_{ob}$  from the bluff bodies respectively for the studied cases. The cross section keeps the same dimensions of boundary layer test section of Polytechnic of Milano, 14 m x 4 m (Bocciolone et al., 2008). On the other hand, three sub-domains (near domain and two far domains) compose the air region solved with the objective of setting different grid parameters and boundary conditions (Fig. 3).

The boundary conditions used for solving the numerical model were defined as follows:

- The wind profile for low turbulence conditions was set at the inlet of flow according to the wind tunnel measurements indicated in Cheli et al. (2011a\b). A uniform profile of 13.89 m/s was imposed from the height of 2 m until the top wall of tunnel considering a scale model of 1:10. The components of wind speed in  $Y$  and  $Z$  directions are zero. The values for the turbulent length scale,  $l$  and turbulence intensity,  $I$  are 0.1 m and 2% respectively.
- An outlet pressure was imposed as a boundary condition at the outlet of flow from the domain. This condition allows the fluid to cross the boundary surface in either direction. The average relative pressure was set to 0 Pa and turbulent properties in back flow conditions were assigned with the values assigned at the inlet boundary.
- A non-slip wall ( $U, V, W=0$ ) was selected as a boundary condition for the solid surfaces (tunnel walls, truck, wind fences and embankment). The log-law region of fluid next to solid surfaces was solved using enhanced wall treatment instead of applying wall function because it is a more accuracy method to estimate the flow variables in this region.

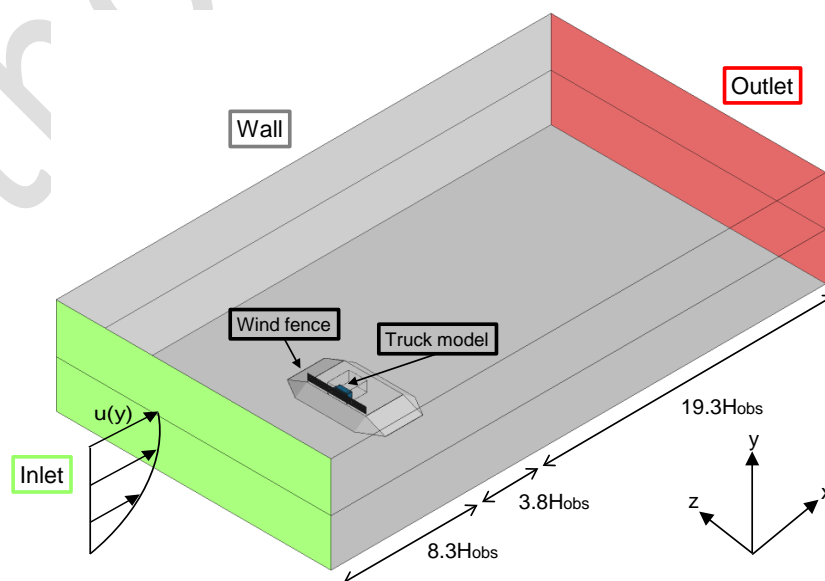
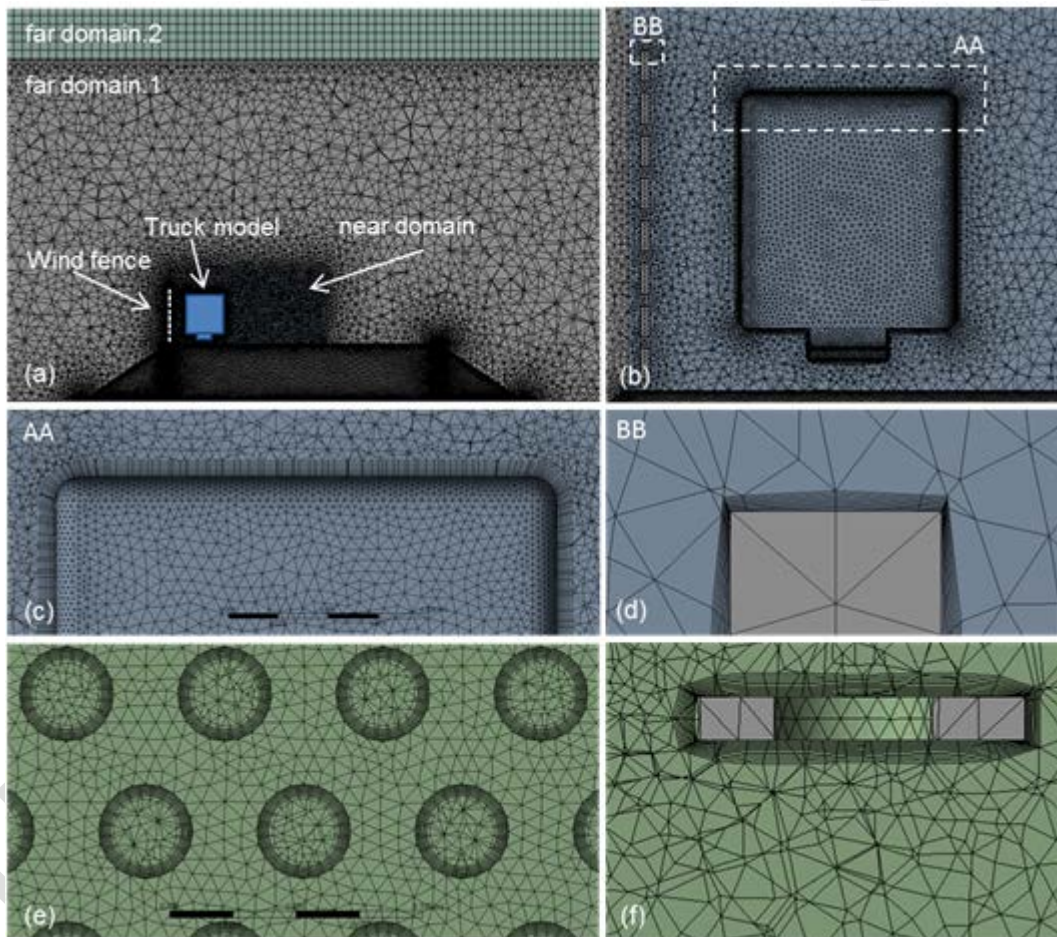


Fig. 3. Geometrical model and boundary conditions.

175 A non-structural grid composed of tetrahedral was built for the far domain.1 and near domain and a  
 176 structural grid composed of hexahedral was built for the far domain. 2 (Fig. 4). The grid of the near  
 177 domain was finer than the far domains in order to capture the high gradients of the flow quantities due to  
 178 the presence of the obstacles found by the air flow. In addition, an inflation grid was used to discretize the  
 179 air region in contact with the truck and fence surfaces without slip due to its high accuracy in boundary  
 180 layer zones (Fig. 4 (c), (d), (e) and (f)). A total of ten inflated layers with a growth rate of 1.05 make up  
 181 the inflation grid, the thickness of the first layer being set to obtain a value of  $y^+ \leq 1$ . The variable  $y^+$  is  
 182 the dimensionless distance from the wall, related to the distance from the wall  $y$ , shear velocity  $u_\tau$  and  
 183 kinematic viscosity  $\nu$  as follows:

$$y^+ = \frac{u_\tau \cdot y}{\nu} \quad (9)$$

184

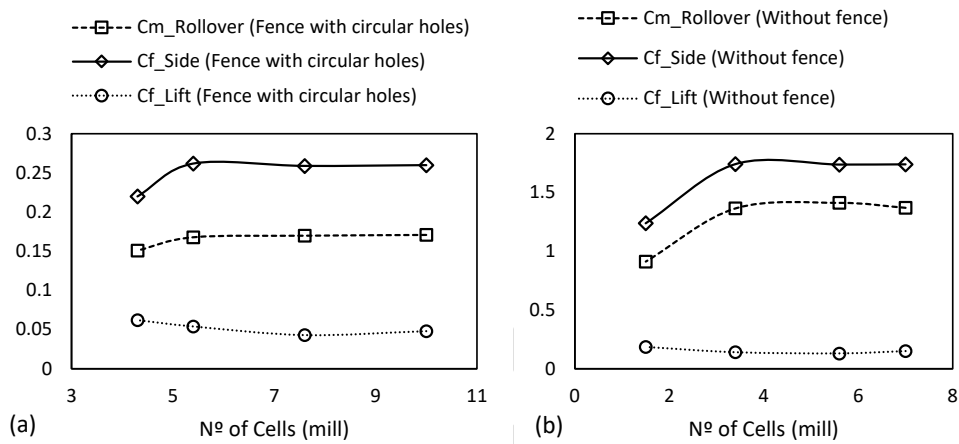


185  
 186 **Fig. 4. Views of the grid in different air regions for the wind fence with rectangular slits and circular holes. (a)**  
 187 **General view of the domains; (b) Grid in the near domain for the fence with rectangular slits; (c) Inflation grid**  
 188 **near the truck surface; (d) Inflation grid near the surface of wind fence with rectangular slits and, (e) and (f)**  
 189 **Inflation grid near the circular hole surface.**

190 A higher accuracy in the results can be obtained by diminishing the cell size in the regions where strong  
 191 gradients in the variables can happen. However, as the cell size diminishes the total number of cells in the  
 192 grid rises and, in consequence the computational cost rises. Therefore, a grid size independence study was  
 193 required to reach an appropriate balance between computational cost and accuracy. The number of cells

194 was varied by means of refinement function acting on curvature surfaces and limiting the size of cells in  
 195 the air regions around the truck and wind fence. Specifically, the aerodynamic coefficients acting on truck  
 196 were calculated for two cases with respect to grid size, when none of the wind fence models was installed  
 197 in the windward region of truck and, when the wind fence with circular holes was installed to protect the  
 198 truck from the wind.

199 The variation of the aerodynamic coefficients as a function of the number of cells is shown in Fig. 5.  
 200 From Fig. 5., it is possible to observe that the aerodynamic coefficients were quite steady for higher  
 201 values of 5.4 mill and 3.4 mill of cells, in the case with the wind fence installed and without fence  
 202 respectively. Thus, one of these two grid setups will be applied for the models where a wind fence model  
 203 is included and the other grid setup for the cases without wind fence.



204  
 205 **Fig. 5. Effect of the number of cells on aerodynamic coefficients acting on the truck for two cases: (a) fence**  
 206 **with circular holes and (b) without fence.**

## 207 2. Results and discussion

208 In this section, the influence of different factors on vehicle stability is analyzed. Particularly, the effect of  
 209 the following factors on aerodynamic coefficients was analyzed:

- 210
- 211 – Reynolds number.
- 212 – Type of wind fence model.
- 213 – Porosity of wind fence models.
- 214 – Truck position on road.
- 215 – Height of wind fence.

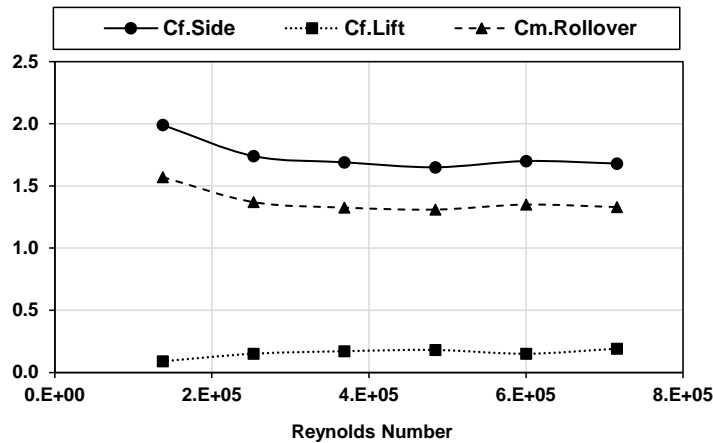
### 216 2.1. Reynolds number effect

217  
 218 The evolution of aerodynamic coefficients acting on the truck model was analyzed for a Reynolds number  
 219 range between  $1.37 \times 10^5$  and  $7.2 \times 10^5$ , in which the flow is still in the incompressible regime. The model  
 220 studied consists on the truck model located on the embankment without the wind fence for a yaw angle of  
 221  $90^\circ$  (crosswind conditions). The values of Reynolds number were obtained by means of the following  
 222 expression:  
 223



$$\text{Re} = \frac{\rho U_{\infty} L}{\mu} \quad (10)$$

224 where the characteristic linear dimension,  $L$  is equal to the reference height,  $H$  used in the aerodynamic  
 225 coefficients. According to Fig. 6, the values of aerodynamic coefficients acting on the truck model are  
 226 quite constant from a Reynolds number equal to  $2.5 \times 10^5$ . In this respect, Cermak (1987) indicates that the  
 227 onset of Reynolds number independence begins at a Reynolds number of  $1.2 \times 10^5$  for bluff bodies.  
 228 Therefore, the dynamic similarity between the 1/10 scaled-down model and the prototype in full scale can  
 229 be considered as satisfied since the value of Reynolds number was  $2.5 \times 10^5$  for every CFD models.



230 **Fig. 6. Relationship between the Reynolds number and aerodynamic coefficients of truck model under**  
 231 **crosswind conditions for the case without wind fence.**

### 234 2.2. Wind fence performance

235 In order to analyze the effectiveness of the three wind fence models to improve the stability of a truck  
 236 model under crosswind conditions, the aerodynamic coefficients acting on the truck were obtained for the  
 237 wind fences proposed and without installing any protection. Specifically, the three wind fence models  
 238 were designed with a porosity (porosity defined as the ratio between the open area and the total area of the  
 239 fence) of 30% and a height of 4m to compare them. Also, a numerical model including a solid fence  
 240 (porosity equal to 0%) was solved to compare its performance with the other types of wind fence. Fig. 7  
 241 exhibits the aerodynamic coefficients obtained for the different cases studied together with the  
 242 experimental values from Cheli et al. (2011b) and Bocciolone et al. (2008). These studies were selected to  
 243 validate the numerical model with experimental data without fence and with fence, since the turbulent  
 244 characteristics of the air region around the truck are quite different when comparing the case without  
 245 fence against the case with fence installed.

247 Moreover, the grid setup applied to solve the numerical models where a wind fence type was included,  
 248 was the same than the applied by Alonso-Estébanez et al. (2016), where aerodynamic coefficients acting  
 249 on bus located on bridge with crash barriers (1.25m of high at full scale and 35% of porosity) installed,  
 250 were obtained in crosswind conditions and compared with experimental data from Dorigatti et al., (2012).  
 251 This along with the fact that the turbulent region in leeward side of the crash barriers should present  
 252 similar characteristic to the region around the truck in some of the wind fence models studied in this  
 253

254 work, it is possible to consider that the grid setup defined in section 2.4., should be suitable to efficiently  
255 solve the cases with wind fences included in the CFD model.

256

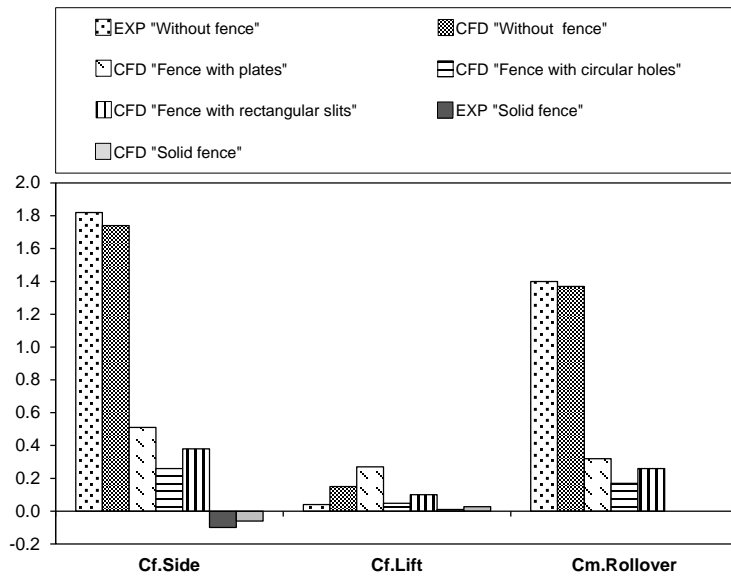
257 The rollover moment is the most influential aerodynamic coefficient on cross-wind stability (Schober et  
258 al., 2010), therefore the results indicate that the wind fence with circular holes shows a better performance  
259 than the other models for this value of porosity (Fig. 7). The rollover coefficient is lower in the case of  
260 installing a wind fence with circular openings than with rectangular openings, this may be due to less  
261 homogeneous distribution of open area. This causes that the contact surface parallel to the mainstream  
262 between the fluid and the wind fence increases, and as consequence higher values of viscous stress are  
263 approached in the air region close to the edge of holes. Therefore, the air flow loses more momentum  
264 quantity as it flows through the wind fence with circular holes, and thus, the side force coefficient acting  
265 on the truck is lower with respect to the wind fence with rectangular slits (Fig. 7). Particularly, the  
266 reduction in the rollover moment coefficients regarding the experimental reference are: 77.14% for wind  
267 fence with plates, 87.86% for wind fence with circular holes and 81.43% for wind fence with rectangular  
268 slits.

269

270 On the other hand, the biggest relative differences between the numerical model and the experimental  
271 data from Cheli et al. 2011b are obtained for the lift aerodynamic coefficient. This could be because all  
272 geometric details of the bottom truck part from experimental study were not kept in the numerical  
273 simulation in order to reduce the grid size and thus the computational cost. As a consequence, the  
274 characteristics of airflow under the truck can vary and the lift force obtained by numerical simulation may  
275 differ from the experimental value. In the case of solid fence, it is possible to observe that the numerical  
276 results are relatively similar to experimental results from Bocciolone et al. (2008).

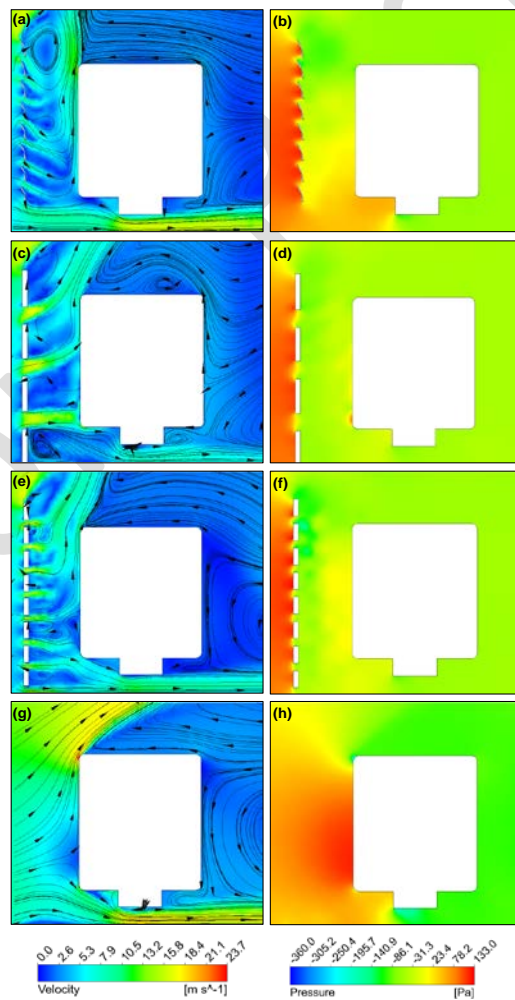
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278 The numerical results in relation to the pressure and velocity in the air region around both the truck and  
279 the wind fence models under crosswind conditions are shown in Fig. 8. From these results, good  
280 performance of wind fence models studied can be appreciated in reducing the aerodynamic loads acting  
281 on the truck with respect to the case without wind fence. The wind fence models cause a reduction of  
282 wind speed in the air region near the windward side of truck, protecting the truck from the impact of high-  
283 speed streamlines (Fig. 8). Specifically, the difference in pressure between the windward side and leeward  
284 side of the truck is slightly higher for the wind fence with plates with respect to the other wind fence  
285 models, as a consequence of this, the side force is also greater according to the results previously  
286 indicated. Also, the lift force of the truck is higher for the model with plates, because the pressure acting  
287 on the bottom left of truck reaches higher positive values due to the air flow is channeled through the  
288 bottom gap between last plate and the ground. As consequence of this, the air velocity in the bottom gap  
289 of the truck approaches higher values for this wind fence model (Fig. 8). On the other hand, the presence  
290 of a wind fence modifies strongly the behavior of air flow before reaching the truck. Specifically, the  
291 wind fence induces a highly turbulent region in the windward side of truck and therefore the pressure  
292 acting on this surface may be negative for low values of porosity, while without the wind fence the  
293 pressure is positive.



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Fig. 7. Comparison of aerodynamic coefficients with perpendicular wind ( $\gamma=90^\circ$ ), obtained by numerical modeling (CFD) for all cases studied and, only by wind tunnel tests for the cases without fence (Cheli et al., 2011b) and with solid fence (Bocciolone et al., 2008).



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Fig. 8. Velocity and pressure contours calculated from numerical model results for the following cases: wind fence with plates (a) and (b); wind fence with circular holes (c) and (d); wind fence with rectangular slits (e) and (f) and without wind fence (g) and (h).

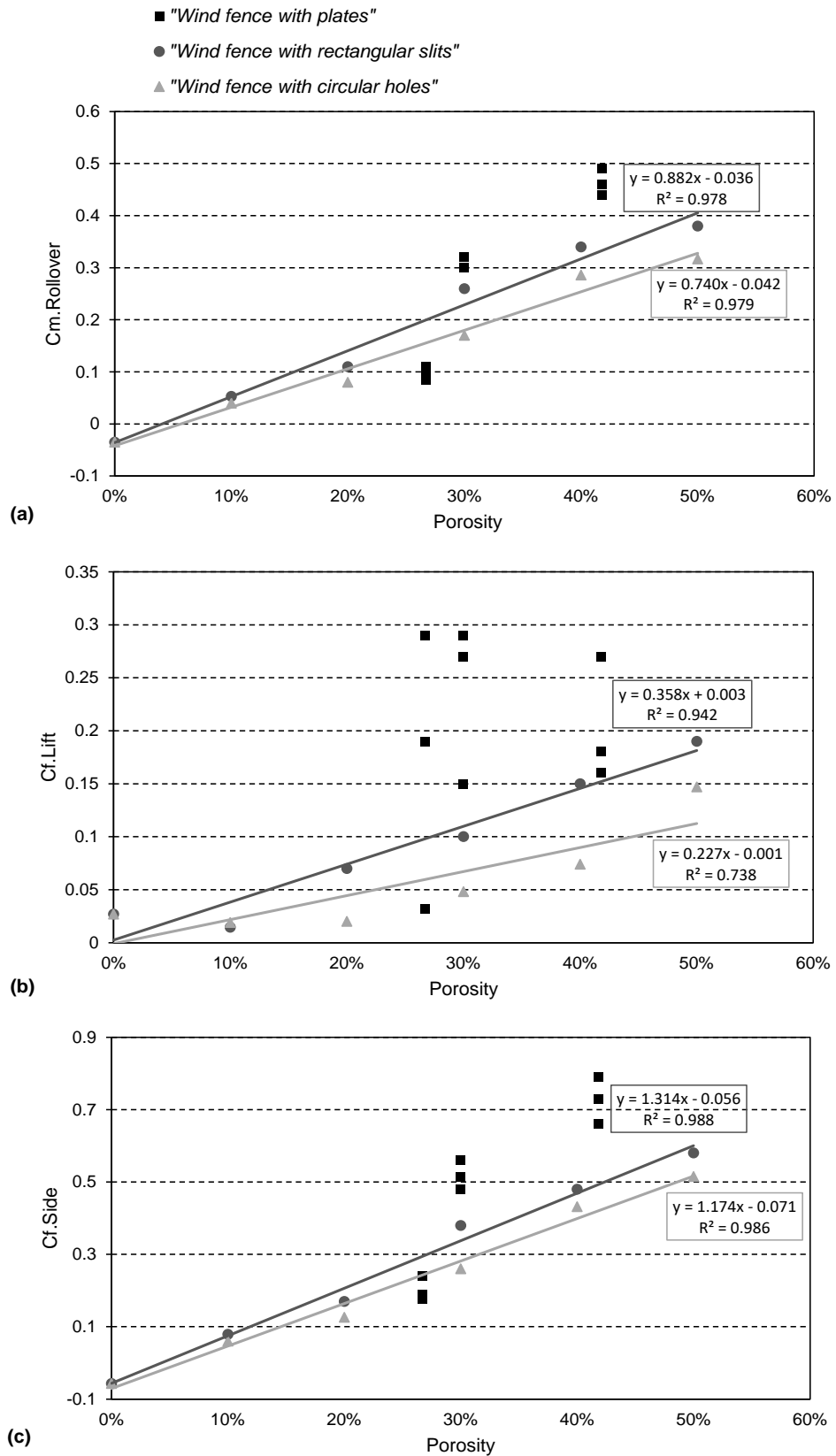
### 2.3. Influence of porosity on aerodynamic coefficients

In this section, the relationships between the aerodynamic coefficients studied and the porosity is obtained for the three wind fence models analyzed. Specifically, the values of porosity studied for the wind fences with circular and rectangular slits were: 0%, 10%, 20%, 30%, 40% and 50%. In these wind fence models the porosity values were adjusted by modifying the diameter of the circular openings and the width of the boards. While in the case of wind fence model with plates the porosity values studied were: 26.7%, 30% and 41.8%. These values were obtained from the design of experiment by modifying the rotation angle of plate parameter,  $\Delta\delta$ . The value of porosity which provides a great protection against a possible rollover accident is considered as the optimum value. Therefore, the aerodynamic coefficients shown in Fig. 9 as a function of porosity indicate the optimum values of porosity are located in the range 0%-10% for the wind fences with circular and rectangular slits. Particularly, this is so for truck positions relatively close to the wind fence as shown in Fig 10. In the case of wind fence with plates, the optimum value of porosity is 26.7% for the range of values studied; however, it is likely that lower values of porosity provide a better protection for relatively small distance between the truck and the wind fence.

On the other hand, when comparing the wind fences models with circular and rectangular open areas the aerodynamic coefficients exhibit similar trends in the porosity range analyzed, however, the circular shape of holes provides a greater reduction of rollover moment in every values of porosity studied. In addition, this differences of rollover moment are smaller as the porosity decreases. In the case of wind fence with plates, the rollover moment coefficient appears to exhibit greater variation with of porosity in comparison with the other wind fence models in the same range of porosity. The intensity of turbulence in the leeward side of the wind fence rises with lower values of porosity and this cause that suction force acting on the windward surface of truck increases. Accordingly, the side force and rollover moment values can be negative for low values of porosity as it is happen in this case (Fig. 9). The rollover coefficient shows a trend against the porosity quiet similar to the side coefficients for all wind fence models studied because the side force has a greater influence in the rollover moment than the lift force. In relation to the lift coefficient, this coefficient decreases as porosity diminishes for the wind fence models with rectangular slits and circular holes but it does not in the case of wind fence with plates.

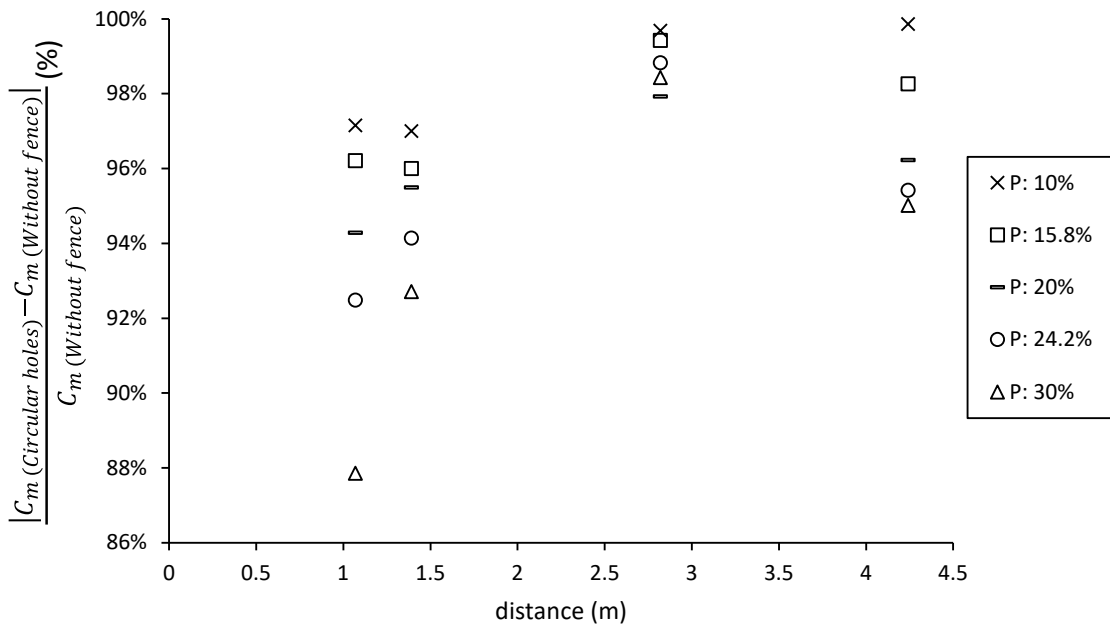
On the other hand, the effect of distance between the wind fence of 4 m height with circular holes and the truck position was also studied for several values of porosity. Specifically, the aerodynamic coefficients acting on the truck were calculated for five values of porosity in the range from 10% to 30% under crosswind conditions. In Fig. 10, the reduction of rollover coefficient with respect to the case without fence as function of the horizontal distance between the truck and wind fence, is shown for the range of porosity indicated. In the reference case, without wind fence, the distance between the truck position and crest of embankment is the same as in the case where the truck position is closer to the fence (1.07 m). From Fig. 10, it is possible to discern that the influence of porosity on rollover reduction is stronger for truck positions closer to the wind fence. The rollover reduction increases with the separation distance between the truck and wind fence, even, the rollover moment coefficient reaches negative values for a

340 distance of 4.24 m where the turbulent flow is predominant. Again, the highest reduction of rollover was  
 341 obtained for the lowest value of porosity, 10% (Fig. 10).



342  
 343  
 344

Fig. 9. Aerodynamic coefficients depending on the porosity for the wind fence of 4 m height and with circular holes. (a) Rollover moment; (b) Lift force; (c) Side force.



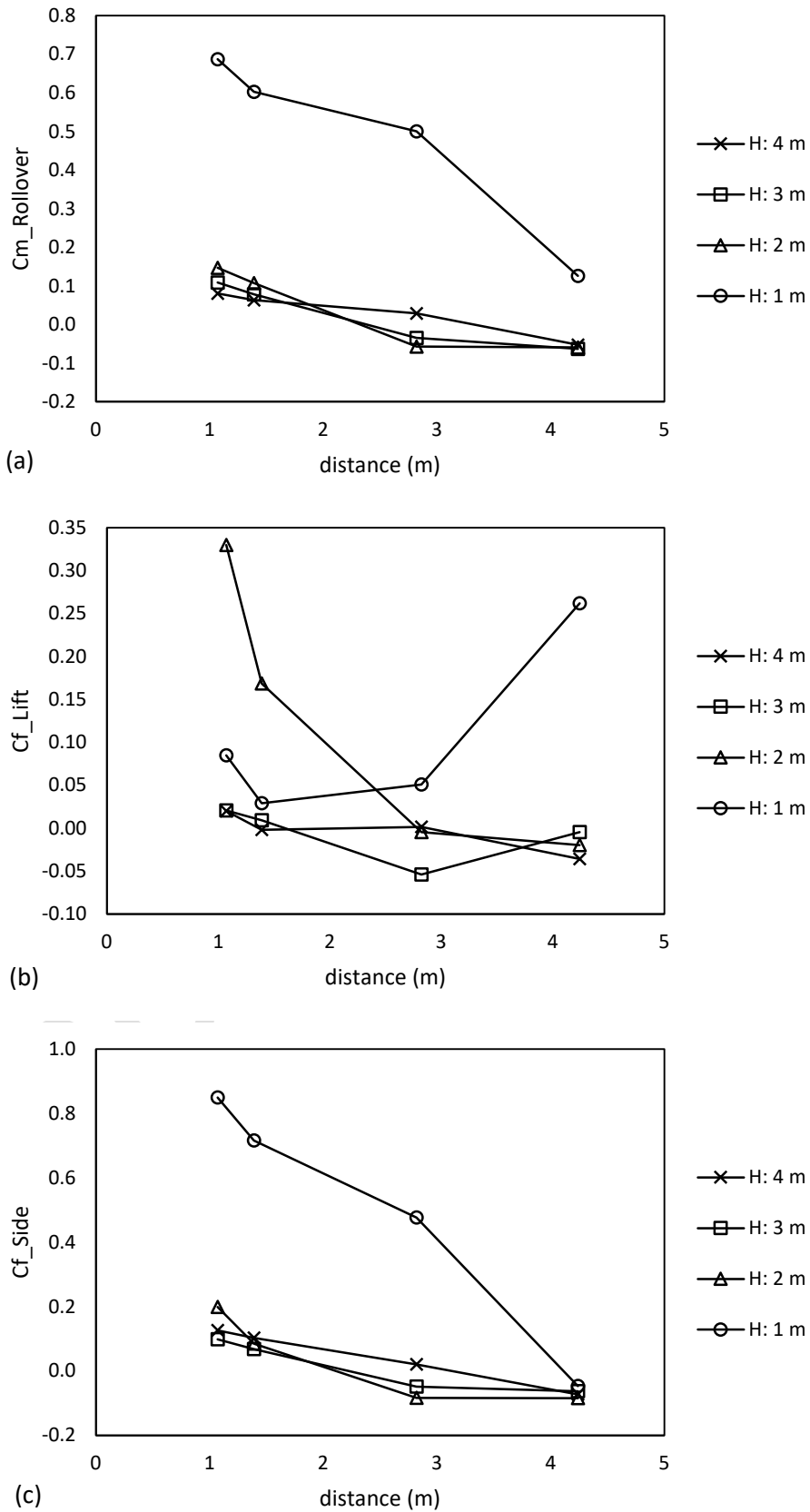
345  
346 **Fig. 10. Relationship between the separation distance between the wind fence and truck position and the**  
347 **rollover reduction for several values of porosity.**  
348

#### 349 **2.4. Effect of the fence height with respect to the truck position**

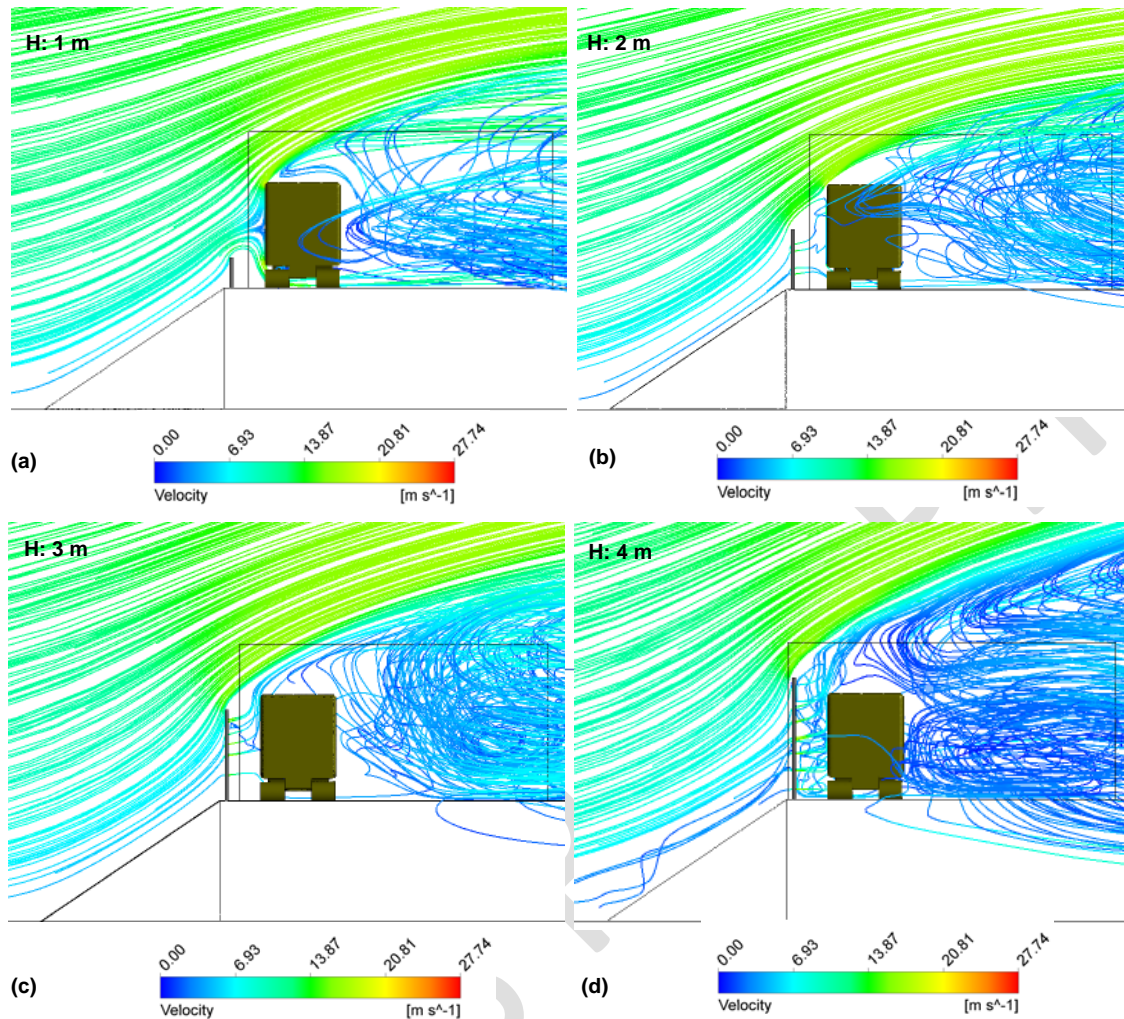
350 Another parameter of the wind fences that was studied in relation to its effect on truck aerodynamic is the  
351 height of wind fence. This parameter could be as important as the porosity of wind fence in the protection  
352 of traffic against adverse wind conditions. The wind fence used for this study was the wind fence with  
353 circular holes keeping its porosity equal to 20% for the four values of height proposed: 4 m, 3 m, 2 m and  
354 1 m. Fig. 11 presents the aerodynamic coefficients of truck as a function of the distance between the truck  
355 position and the wind fence for the fence height values proposed. From Fig. 11, it is possible to observe  
356 that the values of rolover coefficient are quite similar for all height values evaluated except for 1 m of  
357 height. Specifically, the wind fence of 1 m height provides the lowest level of protection against the  
358 crosswind for truck positions relatively close to the wind fence. In fact, the reduction of rolover  
359 coefficient is equal to 78.5% when the wind fence height is increased from 1 m to 2 m for the truck  
360 position closer to the wind fence (1.07 m). Fig. 12 shows that a great portion of streamlines from the  
361 embankment slope hit on the windward surface of truck for a fence height of 1 m, whereas for 2 m of  
362 fence height the streamlines pass mostly over the truck. The rolover coefficient differences obtained for  
363 the wind fence height of 1 m and the other values of height evaluated decrease with the increase of  
364 distance between the fence and truck (Fig 12).

365  
366 Another aspect to be noted is that a wind fence with a height of 2 m can provide a similar level of  
367 protection against crosswind than a wind fence with a height of 4 m, considering both the truck size and  
368 its position on the road studied. With regard to the lift coefficient, the values of this coefficient were quite  
369 similar in the distance range evaluated for 3 m and 4 m of fence height, while strong variations were  
370 obtained in the lift coefficient for lower values of fence height, as shown in Fig. 11. On the other hand,  
371 the effect of the distance between the truck position and the wind fence on the rolover coefficient is

372 relatively strong for the fence height of 1 m and quite softer for the other fence height values evaluated  
 373 (Fig. 12).



374 **Fig. 11. The relationships between the aerodynamic coefficients of truck and the distance in full**  
 375 **scale between the wind fence and the truck position for several values of wind fence height.**  
 376



378  
379 **Fig. 12. Streamlines of velocity field around of truck for four values of wind fence height: (a) 1 m;**  
380 **(b) 2 m; (c) 3 m and (d) 4 m.**

### 381 3. Discussion

382 In this work, the wind fence performance is studied when it is installed in the crest of an embankment, but  
383 if the wind fence was located in a flat ground, lower aerodynamic coefficients acting on the truck should  
384 be obtained, particularly in comparison with the truck position closer to the wind fence. In fact, the over-  
385 speeding coefficient  $f_{EMB,FG}$  used to transform the flat ground coefficients to the embankment coefficients  
386 is 1.23 according to the RIL 80704 (DB NetzAG,2006). Therefore, keeping the same type of wind fence  
387 for both infrastructures (flat ground and embankment), the aerodynamic coefficients acting of truck  
388 should be lower in the flat ground in comparison with truck positions relatively closer to the embankment  
389 crest.

390 On the other hand, aerodynamic coefficients were obtained for a yaw angle of  $90^\circ$  (the wind velocity  
391 relative to the vehicle is perpendicular to vehicle velocity) because is one of the most critical values, as it  
392 is indicated in Cheli et al., (2011b). However, higher values of rollover coefficient could be obtained for  
393 other yaw angle values when a wind fence is installed, as it happens in Bocciolone et al., (2008) where the  
394  
395  
396



397 highest value of rollover coefficient was obtained for yaw angle of 70° using a porous fence. It can be due  
398 to the streamlines of velocity field cover a greater length of embankment slope for this yaw angle value  
399 than in the case of perpendicular flow to the embankment slope, and hence, a higher acceleration of  
400 streamlines is obtained and this counteracts the lack of perpendicular wind component.

401

402 The wind fence can be also used as snow fence, both for avoiding the snowdrift and the formation of ice  
403 on roads, and to improve the visibility of drivers during blizzards (Tabler, 2005). The leeward side of the  
404 wind fence relatively near it is characterized by the vortex presence where the kinetic energy of air flow is  
405 dissipated. In consequence, the air flow losses a predominant wind direction and does not retain enough  
406 kinetic energy to transport snow particles due to its own weight and the snow drops on this region and is  
407 accumulated. The length and depth of the snow deposit zone varies with geometry parameters of wind  
408 fences such as the porosity and the bottom gap (open area between the ground and the fence). On the one  
409 hand, a higher value of porosity increases the air velocity in the leeward region of wind fence and hence  
410 the depth of snowdrift diminishes due to the stronger erosion caused by the air stream while, on the other  
411 hand, the extension of snowdrift region increases. Tabler (2006) indicates that for flat terrain the fences  
412 should be placed at a distance of at least 35 times the fence height from the area to be protected as  
413 measured in the direction of the predominant wind.

414 The bottom gap assists to reduce the deposition of snow in the immediate vicinity of the fence because  
415 the air flow is accelerated when it crosses the bottom gap, delaying the snowdrift and also avoiding that  
416 the wind fence will be buried later. Specifically, the effect of the air flow from the bottom gap is to sweep  
417 away the snowdrift on the road. Accordingly, if the wind fences studied in this work were installed in  
418 embankments where snow is frequently accumulated on the road, porous wind fences including a bottom  
419 gap would be a better option to be installed in comparison to a solid fence. In particular, highest values of  
420 porosity and bottom gap size decrease the snow accumulation rate, however, the effect of bottom gap  
421 on clean region of snow is stronger than the fence porosity according to Liu et al. (2016). The bottom gap  
422 of snow fence must be between 10% and 15% of the total fence height for cleaning properly of snow the  
423 surface immediately downwind of the fence (Sañudo-Fontaneda et al. 2011; Tabler, 2005). Wind fence  
424 models whose main function is to protect the traffic against the wind action, can rise the bottom gap size  
425 to improve the sweeping effect provided of course that a gap size relatively great does not compromise  
426 vehicle stability under crosswind conditions.

427 In this study, the wind fence models are located on the crest of embankment close to the road, without  
428 respecting the distance of 35H (H is the fence height) indicated in Tabler (2006), since these models are  
429 focused on protecting the traffic from the crosswind and, not on storing snow far from the road.  
430 Therefore, in regions where snowfalls are common, the wind fence model with plates can be considered a  
431 better option against the other models, because the plates can be oriented to channel the air flow in the  
432 same direction of bottom flow and strengthen the sweeping effect as it is shown in García Nieto et al.  
433 (2010). This measure should reduce the amount of accumulated snow on roads and to improve the traffic  
434 safety particularly for cold regions around the world.

435 **4. Conclusions**

436 In the present work, the performance of three wind fence models to protect a truck model in crosswind  
437 conditions is analyzed. Furthermore, the influence of characteristic parameter of wind fence (porosity and  
438 height) on the aerodynamic coefficients of truck for four values distance between the truck and the fence  
439 is studied. From the results obtained, the following conclusions can be drawn:

440

441 1. The similarity conditions between the model and prototype were satisfied in the study.

442

443 2. The wind fence with circular holes exhibits a greater efficacy than the model with rectangular  
444 slits for the range of porosity analyzed.

445

446 3. The rollover coefficient acting on the truck decreases when the porosity of wind fence models  
447 studied diminishes. Specifically, the optimum values of porosity are located in the range 0%-  
448 10% for the wind fences with circular and rectangular open areas. In the case of model with  
449 plates, it shows a better performance for the lower value of porosity studied, 26.7%.

450

451 4. The effect of porosity on rollover reduction is stronger for truck positions closer to the wind fence  
452 model.

453

454 5. The rollover coefficient diminishes with the separation distance between the truck and wind  
455 fence, even, a negative value is obtained for a distance of 4.24 m, where the turbulent flow is  
456 predominant.

457

458 6. The rollover coefficient values are quite similar for all values of fence height evaluated except in  
459 the case of wind fence of 1 m height, where the highest values of rollover coefficient are  
460 obtained. In fact, a reduction of rollover coefficient of 78.5% is obtained when the wind fence  
461 height raises from 1 m to 2 m for the truck positions closer to the wind fence.

462

463 7. The rollover coefficient differences between the values estimated for a fence height of 1 m and  
464 for the other values of height (2 m, 3 m and 4m) decrease with the distance between the wind  
465 fence and truck.

466

467 8. The effect of the distance between the truck position and the wind fence on the rollover  
468 coefficient, is quite stronger for the lowest value of wind fence height evaluated. A wind fence  
469 with a height of 2 m can provide a similar level of protection against rollover accident than a  
470 wind fence with a height of 4 m, considering the studied truck size and for truck positions  
471 relatively close to the fence.

472

473 9. The wind fences models installed in the embankments where the snowdrift on road is usual,  
474 should include a bottom gap to minimize the adverse effect both of the accumulation of snow  
475 and the formation of ice on the traffic safety.

476  
477 10. A higher size of bottom gap decreases the amount of snow accumulated in surface immediately  
478 downwind of the fence, however an excessive increase of this gap can compromise the vehicle  
479 stability due to an increasing of aerodynamic loads acting on it in crosswind conditions. Several  
480 researchers recommend a value of bottom gap between 10% and 15% for fences used to control  
481 snowdrift on road.

482

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490

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